Television by Pulse Code Modulation*

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Transmission by pulse code modulation presents inviting possibilities in the field of television in that information may be relayed by many repeater stations without deterioration. In a PCM system, the information signal is periodically sampled and its instantaneous amplitude described by a group of pulses according to a pre-set code. These pulse groups occur at the sampling rate and constitute the transmitted signal. In this process an operation known as amplitude quantization is required.

This paper will include a discussion of time sampling, amplitude quantization, binary coding and decoding of a television signal. The operation of the equipment used to perform these functions is described.

The results obtained with an experimental system for different numbers of digits (i.e., maximum number of pulses per group) from one to five are illustrated by photographs. The television signal used in these tests was obtained from a special low noise film scanner. As was expected, the number of digits required depends upon the amount of noise in the test signal.

THE papers that have so far appeared on pulse code modulation have dealt primarily with the transmission of speech. The present work deals specifically with the problems involved in the transmission of television, but in its general aspects it is pertinent to the transmission of any broadband signal by PCM. The chief difference between a system for telephony and one for television resides in the required speeds of operation. The use of the wide band required for this system would be justified by the well known advantages of a pulse-code system which have been pointed out by Oliver, Pierce and Shannon[1]. Regenerative repetition of the on and off binary pulses at repeater points permits the relaying of the signal to great distances without introducing any significant degradations due to noise or distortion arising in the medium. In addition, the coding process permits the trading of bandwidth for noise advantage on a very favorable basis.

General Considerations

As is well known, PCM is a form of time-division modulation. The information to be transmitted is sampled at regular intervals. This process results in a definite and limited number of amplitudes per unit of time which replace the original wave in subsequent operations. When the sampling frequency is at least twice the highest frequency present in the original wave, the resulting distortion falls outside the desired band and can be removed by a low-pass filter in the output of the system. For a system of fixed

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[1] See "Philosophy of PCM"—Oliver, Pierce and Shannon—*Proc. I.R.E.*, Nov. 1948.

sampling frequency it is also desirable to band limit the input signal to avoid undesirable distortion products due to extraneous frequency components which may be present in the original wave. For a nominal 5 mc television channel the sampling rate used in these experiments was 10 mc per second and the input and output filters passed components of 4.3 mc and attenuated components of 5.0 mc. The sampling process produces a discrete number of samples to be transmitted. For the present case this number is 10 million per second.

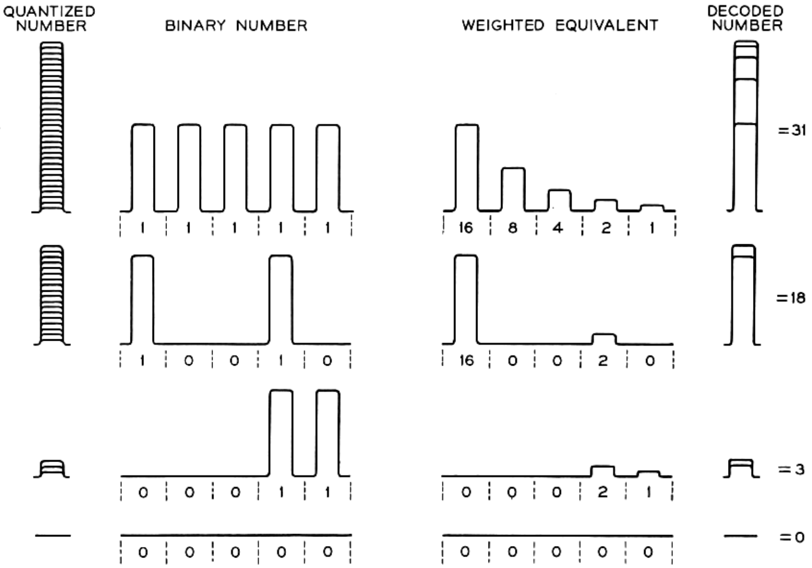


FIG. 1—Five-digit code groups.

Each of these samples may have any value in a continuous range between 0 and a maximum value set by the amplitude range which the system is designed to transmit.

In binary PCM each of these amplitudes is transmitted by a code group of binary digits. As an example, consider a five-digit code which is illustrated in the second column of Fig. 1. Here we have five digits or on-and-off pulses. The maximum number of values that can be represented by these five two-position pulses is 2^5 or 32 values. Examples shown are for amplitudes of 31, 18, 3 and 0. It is easy to see that any other integer value greater than 0 and less than 31 can also be represented by one of the combinations of pulses and spaces. It is also apparent that when all the combinations have been used up no other values can be obtained.

If it were necessary to transmit all of the continuous values present in the sampled wave, it would be necessary to use a large, or even worse, an infinite number of digits. Of course, this is not done. Instead the sampled wave which momentarily may have any value is represented by one of the 32 values that are permitted by the five-digit code. This process is known as amplitude quantization. The quantized amplitudes are shown in the first column of Fig. 1. In the examples shown any number between 17.5 and 18.5 would be represented as 18 and likewise for the other values shown. There is some uncertainty as to the correct value exactly one-half way between permitted values. Here an arbitrary choice is much to be preferred to faulty operation which may give a large error signal. More will be said about this point later.

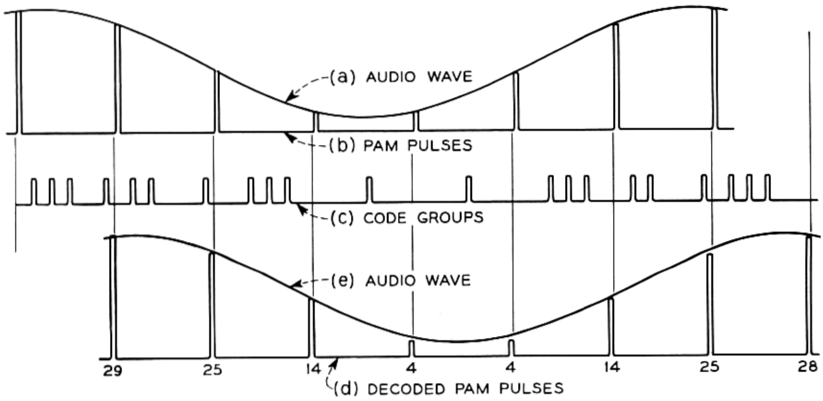


FIG. 2—PCM wave forms.

Each of these code groups, here illustrated as a 5-digit group, represents a single sample of the ten million per second that are needed to represent the television signal. These digits may be transmitted over a single circuit. Figure 2 is an example of this method of transmission for an audio wave *a*. The samples are represented by the PAM wave *b*. The code groups are shown in the wave *c* while the decoded pulses are shown on the wave *d*. The original audio wave, delayed by one sampling interval, is shown as wave *e*. It will be noted that the quantized PAM pulse waves *d* do not fit exactly on the curve. This is the result of the quantization process previously mentioned.

For a five-digit 4 kc telephone channel forty thousand digit pulses per second are used in the transmission medium. For television, the same wave forms apply, and a five-digit 5 mc signal uses fifty million pulses per second in the transmission medium. Figure 2 illustrates a PCM system where the digit pulses are sent on a time-division basis. It is not necessary to do this, however, since the digit pulses may be sent over separate wire or frequency-division carrier circuits. In the experimental setup used in these studies each of the five digits is transmitted over a separate wire circuit. The total bandwidth required in the transmission medium is essentially the same for both methods of transmission. A single one-way television circuit for five digits would require from 50 to 100 megacycles bandwidth in a microwave system. The actual required band would depend upon the state of the art and the complication permitted in the repeater equipment.

From many points of view the transmission medium is the most important part of the system. In non-regenerative systems, for example in the carrier system used in present day coaxial cable transmission, most of the distortion and noise that appears in the final output is the additive resultant of a large number of small contributions arising in the individual repeater links that make up the complete transmission medium. It is easy to see that, for this method of transmission, each repeater link must be much better than the overall system. For a signal that is sampled and quantized in amplitude, however, it is possible to generate a new signal at each repeater which is essentially perfect. In the absence of noise the quantized signal would have one of the permitted amplitudes at the sampling time. A small amount of noise will change this situation so that the amplitude will not be exactly the correct value at the sampling time. As long as the noise or other disturbance is not too great, it is possible to requantize the signal and to transmit the correct amplitude at the sampling times. This process which is known as regeneration can be used for any type of signal that has been sampled and quantized in amplitude. For a system using binary pulses where only two levels are present, the regenerative process is technically possible. Regenerative repeaters would transmit new pulses, which would be accurately timed and properly shaped. As long as the noise is kept below a threshold value, the noise would not accumulate from link to link and the final decoded signal would be of the same quality as one obtained from a monitor located at the transmitter.

This means that the quality of the final output of the system depends upon the size of the time and amplitude quanta used in the PCM system. In other words, the final quality depends upon the sampling rate and the number of digits used and not upon the length of the system.

The last two columns of Fig. 1 show how the digit pulses can be decoded to produce the output signal. The decoder produces the weighted equivalents of the digit pulses which are then added for each code group. Each of these summation pulses represents one of the input samples in a quantized form. These summation pulses are then passed through an appropriate low-pass filter to the output of the system.

Description of Experiments

The experiments to be described were confined to tests with a transmitting terminal connected to the receiving terminal by short coaxial transmission lines. The transmitting terminal performed the functions of sampling, quantizing and coding, while the receiving terminal decoded the PCM signal. No regenerative repeaters were included since they are not necessary in tests designed to evaluate the fundamental limitations of sampling and quantizing of a television signal.

Figure 3 gives a block diagram of the system used in these experiments. The input filter band limits the signal so that the highest frequency is less than one-half of the 10-megacycle sampling rate. The input sampler samples the wave and holds the amplitude value obtained until the next sampling interval. It uses the same type of circuit as that described in the paper by Meacham and Peterson in *The Bell System Technical Journal* for January

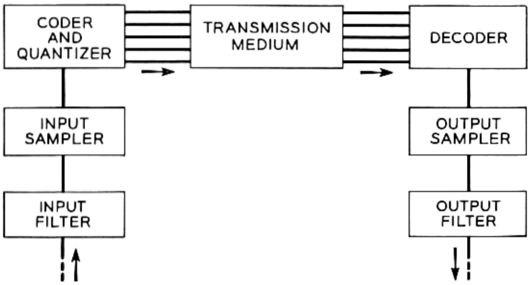


Fig. 3—Block schematic of PCM system.

1948. In general, much of the circuitry described by them has been used in this equipment, but the units of course function at greatly increased speeds.

The coder and quantizer use a coding tube which produces the code simultaneously in five-digit output circuits. Quantization is accomplished by using a special code, together with suitable slicing units in the output of the digit amplifiers. Further discussion of the coder and quantizer will be given in connection with Fig. 4.

In these experiments the transmission medium consisted of an appropriate number of wire circuits, no regenerative repeaters being used. At the receiver, a decoder regenerates the pulses and adds the weighted digits to obtain the quantized PAM signal, as already shown in Figs. 1 and 2. The output sampler is similar to the one used at the input. It will be recalled that step samples are produced, i.e., the signal is sampled at the beginning of each interval and this value is held until the next sampling time. The output filter band limits the signal and removes extraneous components above 5 mc, particularly the 10 mc sampling frequency. As is well known, these filters should have good phase response if they are to be used for a television signal.

The physical equipment used in this experiment is housed in three seven-foot cabinet relay racks. One bay contains the sampler, the push-pull amplifier for driving the deflection plates of the coding tube, the coding tube, the digit amplifier and slicers, and finally the translator. Another bay contains the decoder, output sampler, attenuators, patching panel, output filter and other test gear. The last bay contains the regulated power supplies.

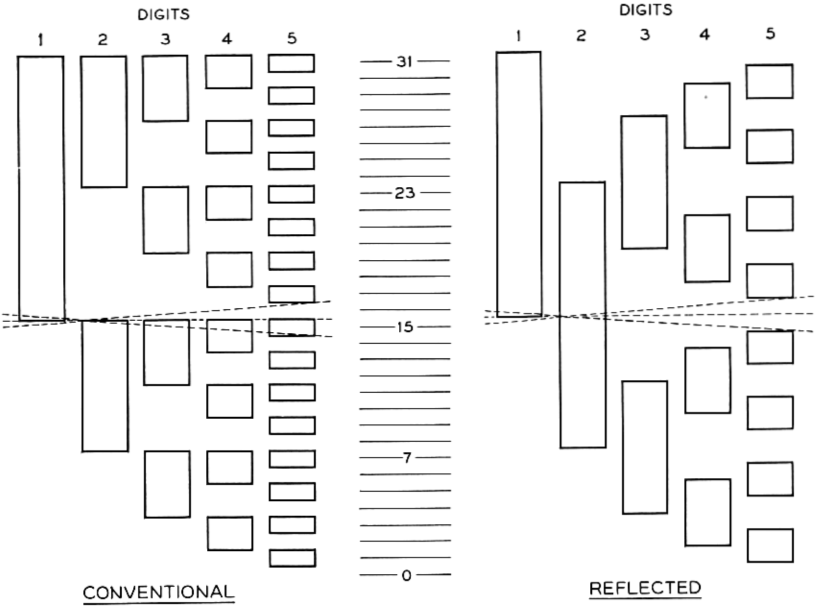


FIG. 4—PCM code plates.

CODERS AND QUANTIZERS

We return now to further consideration of the coder and quantizer. The coding tube used in these experiments was developed by Mr. R. W. Sears. It is similar in many respects to one previously described by him in *The Bell System Technical Journal* for January 1948. The older tube produced the code on a time-division basis, while the new tube produces the code simultaneously on a plurality of output digit collectors.

The time-division coding tube which was used by Meacham and Peterson in the 96-channel multiplex system first quantized and then coded the signal. The simultaneous coding tube uses a different code which does not require a quantized input. The encoded signal is subsequently translated into the conventional binary code.

The coder and quantizer are probably the most important parts of the terminals of a PCM system. The following discussion of the two types of coding tubes will illustrate how they function and show how the new tube can function at the greater speeds necessary for television.

Consider the code plate on the left side of the next figure (4). This plate gives the conventional binary code as discussed in connection with the first figure. In a time-division coding tube a point beam is used. It is deflected vertically by the output of the sampler. After the beam has settled down to its proper position, which corresponds to the quantized signal amplitude it is swept across the code plate. An output collector is used which covers the back of the code plate. If the beam goes through a hole in the code plate a pulse is produced; if it is stopped by the code plate no pulse is produced. By this means a code group is produced on a time-division basis for each sample.

As long as the beam does not fall on the edge of a hole, this arrangement functions satisfactorily. Now consider the case where the beam sweeps across the set of edges corresponding to the amplitude 15.5. It is seen that, by a slight misalignment of the code plate and the horizontal deflecting plates, the beam could produce either the code group corresponding to 31 or to 0 depending upon the way the deflection axis is tilted with respect to the code plate. This would result in an error equal to one-half of the total amplitude range of the system. Corresponding errors of smaller magnitude are possible for other levels. In all cases this type of error results for signals which have amplitudes one-half way between values permitted by the code.

Errors of this sort can be avoided by quantization of the signal before the coding. This is accomplished in the earlier tube by using the output from a mesh of grid wires in a feedback arrangement. The wires of the grid overlap the edges of the holes in the code plate. When the beam hits one of these grid wires, a current is fed back into the input which causes the signal amplitude to change in such a way as to move the beam between the grid wires. After a short interval the beam settles down in a quantized condition. Then the beam is swept across the code plate. If the beam tends to become misaligned during the deflection process, the feedback from the grid wires corrects this condition and an accurate code is produced. Because of the time required for the feedback process, this method of quantization limits the number of samples that can be coded in a given time.

Another factor which limits the speed of this type of coder is the time required to sweep the beam across the code plate.

It is apparent that the time required to register the code could be reduced if all digits were produced simultaneously. In this type of coder a line beam is used which covers the full width of the code plate and the code is registered simultaneously on a plurality of digit collectors, one collector being used for each digit of the code. This is one of the features that was included in the coding tube used in these experiments.

In the new tube the time required for quantization by feedback has been avoided by using a different type of code which avoids the large errors which are present in the conventional binary code for amplitude values one-half way between the integer values permitted by the code. This new code, here called the reflected binary code, is shown on the right side of Fig. 4.

For present purposes it should be noted that at points one-half way between integer values the beam intersects only one edge in any code group. Further, if the deflection axis is tilted so that an incorrect code group is indicated, the resulting error is only one quantum level, instead of a much larger value possible with the conventional binary code.

In practice, even if the beam is properly lined up, there will be times when the output for the digit in which the beam intersects an edge will be between zero and full output. Since this digit must be unambiguously represented either by a full pulse or no pulse, it is necessary to make a choice and quantize the particular output under discussion. The output of the digit collectors is amplified and the final quantization of any uncertain digit is done by a slicer which is in the output of each digit amplifier. Use of this code thus localizes final quantization to within a single digit, and an arbitrary choice results at most in an error of one quantum level.

The use of the reflected binary code for PCM applications was suggested to the writer by Mr. F. Gray. As mentioned before, this code is translated to the conventional binary code. The translator used in these tests was designed by Mr. R. L. Carbrey who developed it specifically for this experiment.

Results of Experiments

We now pass on to some of the results obtained with this system. Figure 5 should help in understanding the results shown in the remaining figures. It shows a triangular wave which has been analyzed into the three "on" and "off" rectangular waves shown in the bottom part of the figure.

In this paper we shall follow the convention that the digit of largest amplitude is the first digit, the next largest digit is the second digit and so on. By this convention the first digit is $\frac{1}{2}$ of the total amplitude range, the second digit $\frac{1}{2}$ of the first, or $\frac{1}{4}$ of the total range. Thus, the amplitude of any given digit would be $\frac{1}{2^n}$ of the total amplitude range.

It is convenient to think of the first digit as a first-order approximation to the original in terms of the rectangular waves. The second digit gives a second-order correction to add to the first digit, and the third digit gives a third-order correction to add to the first and second digits.

The rectangular waves, of course, are the envelopes of the pulses that are transmitted over the various digit channels. Because the respective values represented by the various digits are once and for all known, it is not necessary that the amplitudes with which the pulses are transmitted be equal to the values which they represent, but they may to advantage be sent with the same amplitude in all of the digit channels. At the decoder the relative

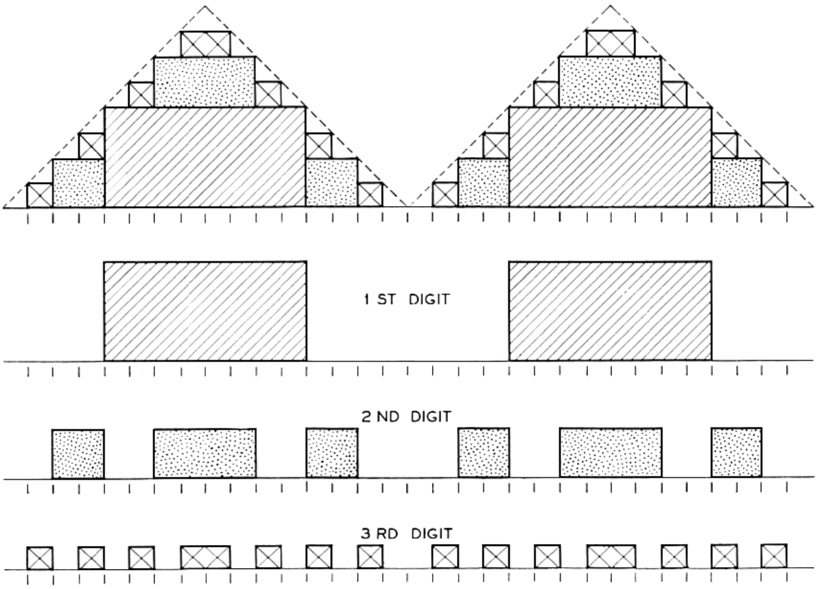


FIG. 5—Rectangular wave approximations.

amplitudes of the digit channels are restored according to the coding convention and the results added to obtain the rectangular wave approximation to the original wave. It is seen that the first three digits give a fair approximation to the original wave. More digits, of course, would improve this approximation.

In general terms, from this point of view, the coder is an analyzer which determines the best approximation to the information wave in terms of a series of rectangular waves of decreasing amplitudes. The decoder is a synthesizer which approximates the original wave by adding the rectangular waves obtained from the coder. The coding convention allows the derived rectangular waves to be transmitted with the same amplitude for all the

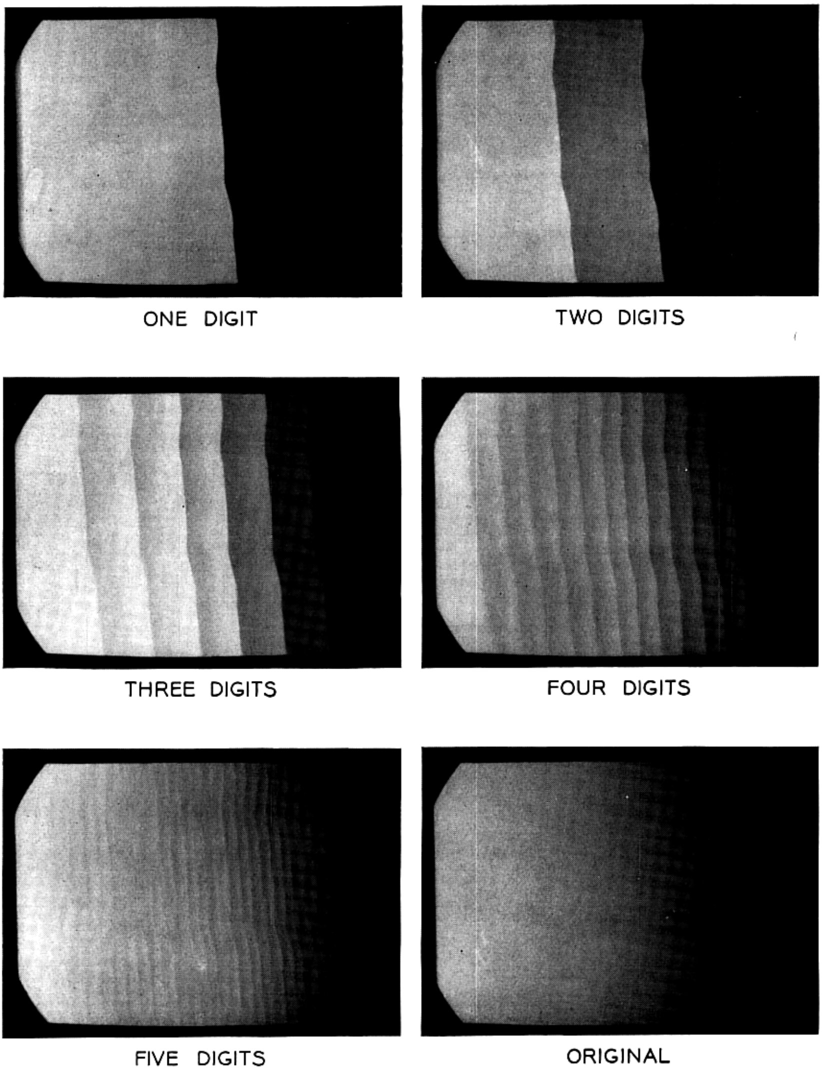


FIG. 6—Test signal, Density wedge: one to five-digit transmission.

digits. The remaining figures show some results obtained by transmitting a television signal through the PCM system described in the first part of the paper.

Mr. B. M. Oliver and others of the television group of The Bell Telephone Laboratories have developed a special low-noise film scanner that provides an excellent test signal. This equipment includes a rooter which, in combination with the expansion of the kinescope, results in an overall linear system. This method of operation, as is well known, results in a wide range of tone values between black and white. The PCM system used, employed steps of equal size; in other words, within the limits of the quantum steps it is a linear system. The combination of the signal from the film scanner, including the rooter, and the linear PCM system, followed by an expanding viewing tube, results in an overall system which employes the limited number of steps in the PCM system to essentially optimum advantage.

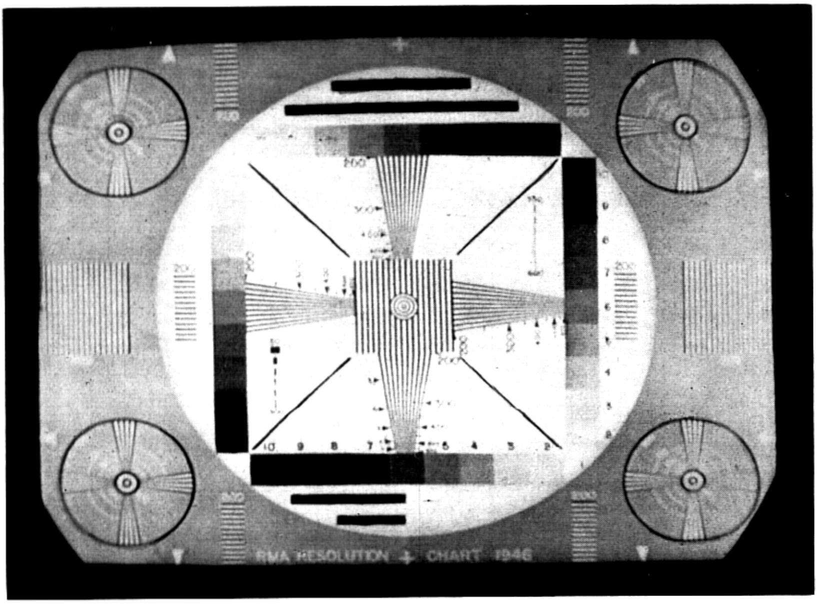


FIG. 7—Test signal, RMA test chart: five-digit transmission.

While in practice, synchronization would probably be derived from the code pulses, for the purposes of this experiment it was not necessary to transmit the synchronizing pulse through the PCM system. Synchronization of the monitor was obtained by a separate path. This was done, since in an operating system it would not be necessary to use more than one or two levels to send the synchronizing pulse as compared with 25% or more of the levels that would be necessary in an unmodified standard television wave-form.

The pictures shown on the figures were taken with a one-second exposure. It will be realized that in a photographic still picture obtained in this manner the exact effect in the viewing tube cannot be conveyed because it is not possible to see motion due to noise.

Figure 6 shows the results obtained using a special test signal for five different PCM systems. The five PCM systems are those which result for

Fig. 8—Test signal, model: one to five-digit transmission.

one digit, for two digit, for three, four and five-digit transmission. The test signal for these pictures was an electrical saw tooth wave derived from the horizontal sweep generator. It will be noted that the linear input signal results in an amplitude quantized output signal. The one-digit system sends

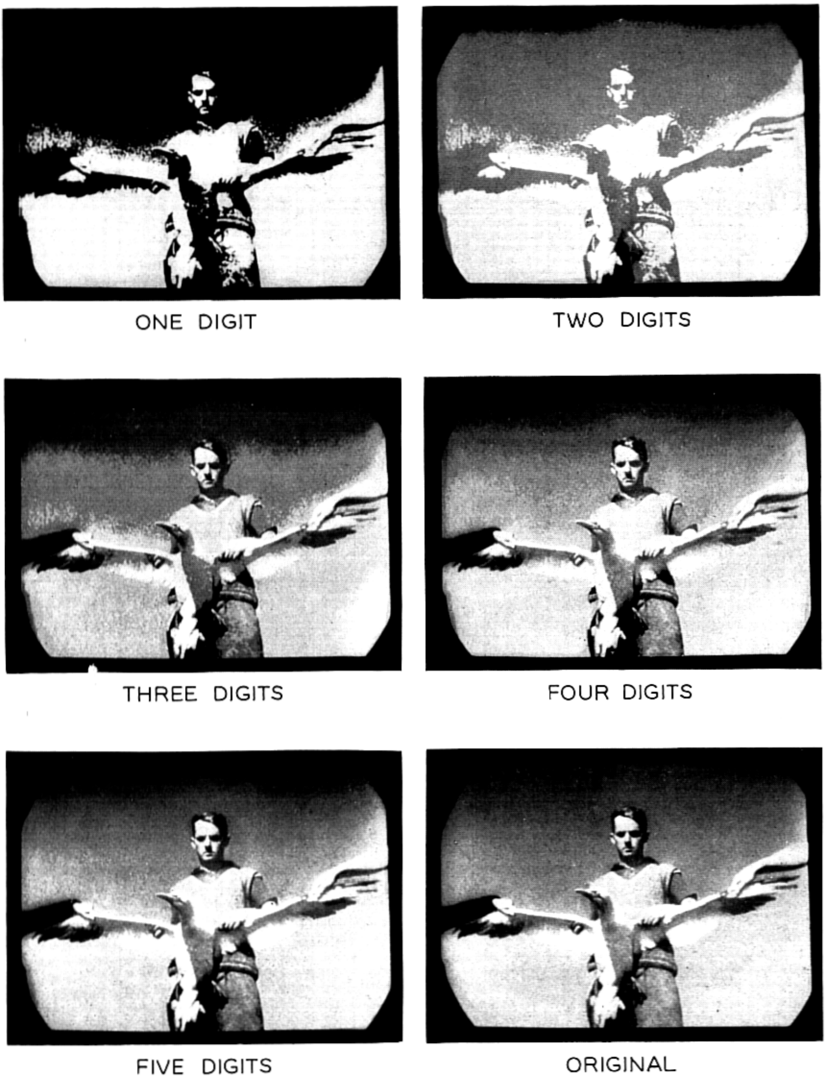


FIG. 9—Test signal, boy and bird: one to five-digit transmission.

two levels, black and middle grey. The two-digit system sends four levels, the three-digit system sends eight levels and the four and five-digit system

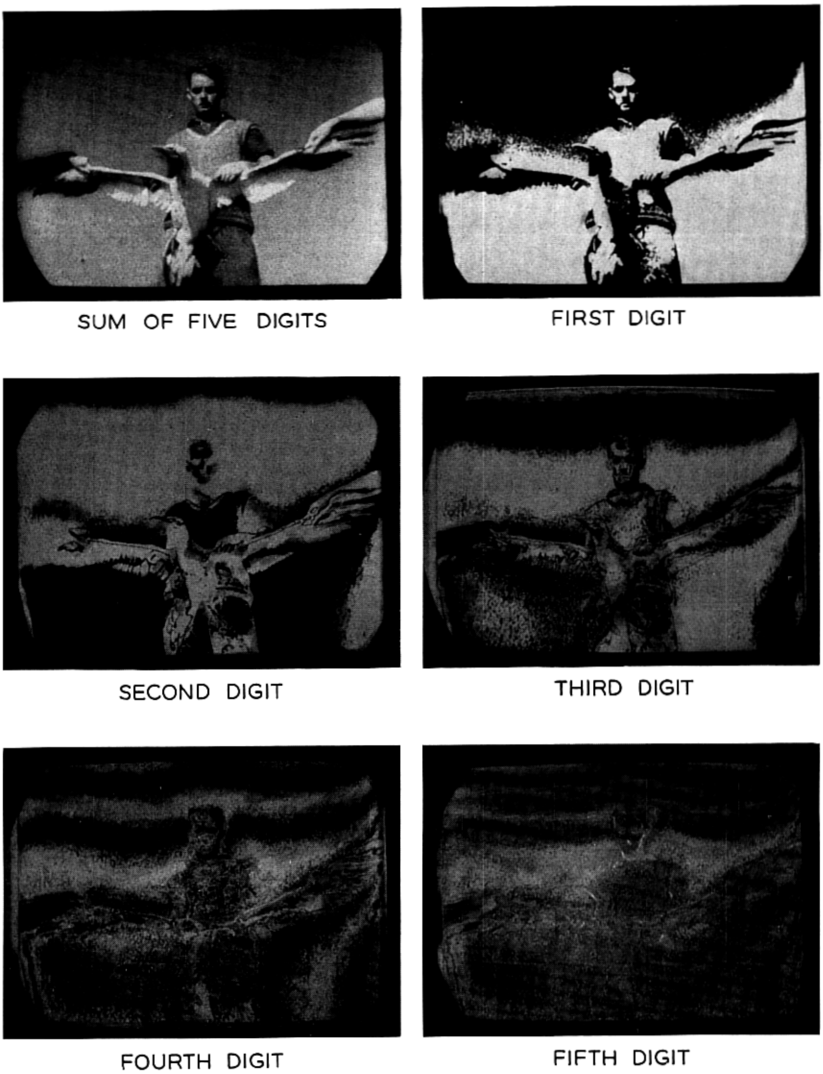


Fig. 10—Test signal, boy and bird: single digits, one through five.

sends sixteen and thirty-two levels. The original, of course, is not quantized and shows a smooth graduation from black to white. It is, however, band limited by the input filter.

The steps in the five-digit system are even more clearly visible on the picture tube. During some tests in which random noise was added to the test signal, it was found that the sharpness of the contour edges was destroyed by random noise when the ratio of the peak-to-peak signal to rms noise was 60 db. For the five-digit picture the smearing of the edges was about one-tenth of the distance between the contours. Other tests which will be described later suggest that the contours for the five-digit thirty-two level system would be masked with an input peak-to-peak signal to rms noise ratio of 40 db.

The writer is not aware of a television system that is capable of generating a signal with a peak-to-peak signal to rms noise ratio of 60 db. However, if such a system were available, these results indicate that an eight- or nine-digit PCM system would be needed to avoid appreciable degradation of the 60 db signal.

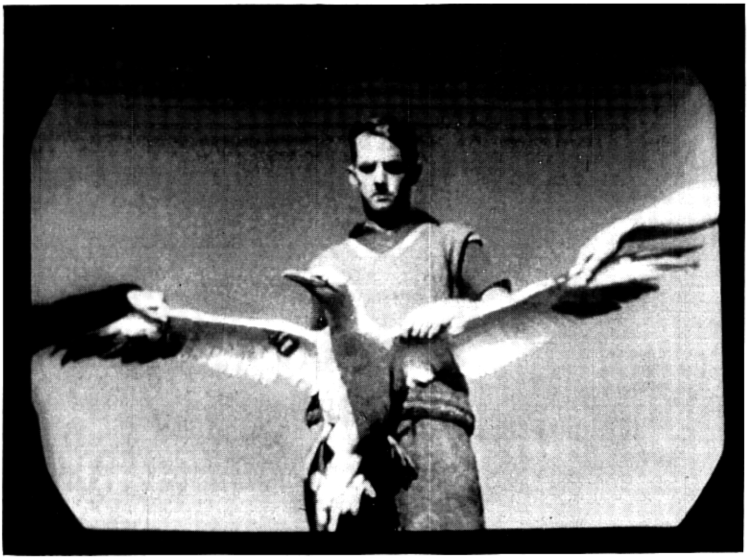
Figure 7 shows the results for an RMA test chart with five-digit PCM transmission. The resolution is limited by the input filter, the film scanner having a resolution corresponding to about 10 megacycles. Using the test pattern for a signal, careful comparison of the band limited transmission with and without the PCM system showed only small defects in the PCM transmission.

When the PCM transmission is seen on the television screen, the contour effects which are strikingly apparent for one, two, and three digits are hardly noticeable for five digits. Figure 8 illustrates this performance as well as is practical with photographic reproduction. About one digit is lost, and the three-digit printed reproduction shows the contours with about the same distinctness as four digits when viewed on the television screen. This statement applies in general to all of the printed reproductions.

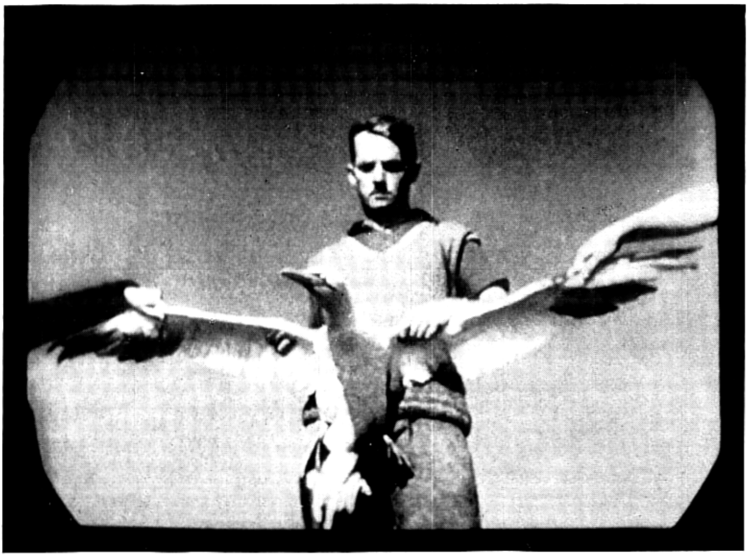
Figure 9 shows the same results for a different subject. The contour effects for a transmission system using a small number of digits are particularly apparent in the sky.

Another method of presenting the results is shown in Fig. 10. In the previous pictures the results have been presented for complete systems using one, two, etc., up to five digits. In Fig. 10, however, the transmission of each of the five digits is separately illustrated. Except for the 5th digit, for which this was not possible, an attempt was made to reproduce the pictures with equal contrast between black and white. The large amount of detail present in the fourth and fifth digits is particularly striking. The sum picture was obtained with proper weighting of the all five digits as discussed earlier in the paper.

The remaining figure (11) illustrates the effect of adding noise to the input to reduce the contour effects. From these photographs it appears that adding noise has been definitely helpful in this respect. However, a penalty is paid for this result. The photographic process reduces the effect of noise by



FOUR DIGITS



FOUR DIGITS PLUS NOISE

FIG. 11—Test signal, boy and bird: with and without added noise.

integration and the picture observed on the monitor for the added noise case was definitely more "noisy" than the other picture. Even so, most observers agreed that in general the adding of noise was desirable for a system using a small number of digits.

Acknowledgments

Many people contributed to the success of this experiment. Mr. O. E. DeLange and Mr. A. F. Dietrich worked along with the writer in the design, building and testing of the equipment. Mr. R. W. Sears, Mr. R. L. Carbrey and Mr. L. A. Meacham should be specially mentioned in connection with the design of the equipment, and Mr. B. M. Oliver assisted in the television tests. Mr. J. C. Schelleng assisted with suggestions and guidance.